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An Introduction to Detonation and Blast for the Non-Specialist

C.R. Wilkinson and
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ABSTRACT

Blast effects can play a significant role in target damage. This report gives an overview of how blast waves are formed and describes methods for scaling blast overpressure. The aim is to provide a concise overview of blast for the non specialist.

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An Introduction to Detonation and Blast for the Non-Specialist

Executive Summary

Blast effects can play a significant role in target damage, hence a general understanding is useful when evaluating weapon performance. This paper arose out of a meeting on blast and fragmentation effects when a researcher with a non-blast background expressed the need for a brief overview of blast effects and terminology for non-specialists.

This report describes how an explosive detonates, and produces a blast (shock) wave. The physical processes involved, and some of the common terms used in the field are explained. In addition, scaling of blast overpressure and methods for determining blast from fragmenting munitions are discussed also.

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1. Introduction

This paper is a review of detonation and blast and is written for the non-specialist. The review is based on reading performed by the authors. There exist several good books on explosive effects, notably *Explosives Engineering* by P. Cooper[1]; *Explosive Shocks in Air* by G. Kinney and K. Graham[2], *Explosions in Air* by W. Baker[3] and *Explosion Hazards and Evaluation* by Baker *et al.*[4]. A computer program called ConWep[5], produced by the US Army Waterways Experimental Station, provides simple conventional weapons effects calculations that are based on the curves and figures in the report TM 5-855-1, *Fundamentals of Protective Design for Conventional Weapons*[6], which is included as part of the online documentation in ConWep.

2. Detonation

The purpose of this section is to describe the process of detonation of high explosives. Generally explosives are initiated through the use of a detonator and booster charge. The role of the detonator and booster is to create a shock wave of sufficient energy to initiate a sustained chemical reaction in the explosive. Often, detonators alone will not produce enough energy to initiate explosive charges directly, but they will however produce enough energy to initiate a booster. In turn, the booster creates enough energy to initiate the explosive.

The shock wave created by the booster compresses and raises the temperature of the explosive above the ignition point of the material, initiating a chemical reaction within a small region just behind the shock wave, known as the reaction zone. Detonation occurs when the reaction propagates through the explosive at shock velocity. The propagation of the reaction through the explosive is referred to as the detonation wave. Figure 1 shows the pressure variation as a function of distance as a detonation wave moves through the explosive. The rapid rise in pressure, known as the Von Neuman spike, is what brings on the reaction. The CJ (Chapman-Jouguet) point represents the state of the detonation products at the end of t he reaction zone [1].

Hot gaseous detonation products are produced from the reaction occurring in the reaction zone. These gases expand and generate a rarefaction wave that moves forward into the shock. The expansion of the detonation products is described by the Taylor wave. The shock front, reaction zone, and leading edge of the rarefaction wave are all in equilibrium, moving at a constant velocity known as the detonation velocity. The exact detonation velocity will depend upon the explosive material, as well as physical parameters such as density and degree of confinement of the explosive [1].

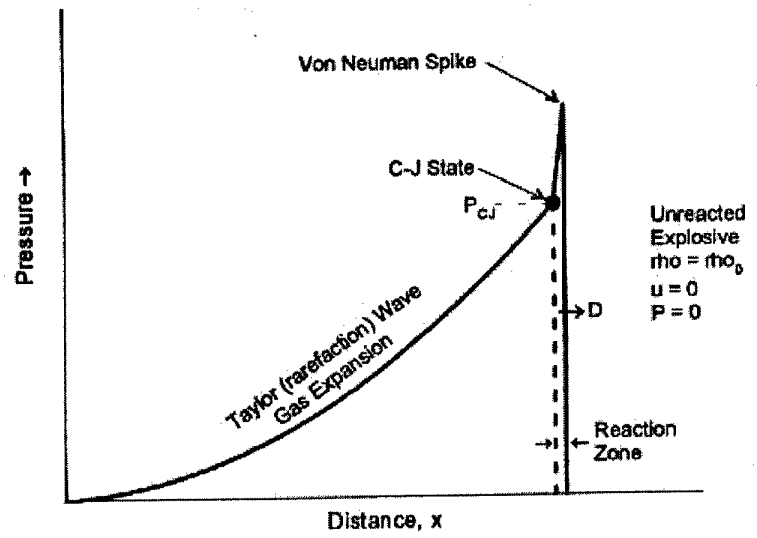

Figure 1. Pressure vs distance diagram of a detonation wave [1].

The majority of explosives are formed from the elements Carbon, Hydrogen, Nitrogen and Oxygen (CHNO). Explosives release energy through oxidation reactions. When a fuel burns with oxygen to its most stable oxidised state, the energy released is called the heat of combustion, which represents the maximum amount of energy that may be released in an explosion. However many explosives do not contain sufficient oxygen to reach full combustion, and thus the heat released during detonation, known as the heat of detonation ΔH_d^0, is less than the heat of combustion. A theoretical estimate of the heat of detonation, accurate to about 10%, may be obtained through tables of heats of formation. The heat of formation, ΔH_f^0, is the heat of reaction (enthalpy change) in making a particular compound from elements, where both elements and compound are at standard state conditions. The heat of detonation ΔH_d^0 is simply the difference between the heat of formation of the detonation products and the initial explosive.

$$\Delta H_d^0 = \Sigma \Delta H_f^0 (\text{detonation products}) - \Delta H_f^0 (\text{explosive})$$

Note that experimental values should be preferred over such theoretical estimates, as the detonation physics (initial density, temperature and degree of confinement) will influence the actual amount of energy released [1].

The general chemical formula for all CHNO explosives is $C_xH_yN_wO_z$. During detonation, the explosive breaks down and the component elements Carbon and Hydrogen react with the available Oxygen [1].

The general reaction product hierarchy is given below and represents a rule of thumb [1]:

1. All the nitrogen forms N_2.
2. All the hydrogen is burned to H_2O.
3. Any oxygen left after H_2O formation burns carbon to CO.
4. Any oxygen left after CO formation burns CO to CO_2.
5. Any oxygen remaining forms O_2.
6. Any excess carbon forms C (solid).
7. Traces of NO_x (mixed oxides of nitrogen) are always formed (less than 1%).

Oxygen balance (OB) provides an indication of the relative amount of available oxygen and is usually expressed in terms of the weight percent of excess oxygen compared to the weight of explosive $C_xH_yN_wO_z$:

$$OB\% = 100\frac{AW(O)}{MW(explosive)}(z - 2x - y/2)$$

where the atomic weight of oxygen, AW(O), is 16 and the molecular weight of the explosive, MW(explosive) is the sum of atomic weights.

$$MW(explosive) = 12.01x + 1.008y + 14.008w + 16z$$

As an example, TNT has the formula $C_7H_5N_3O_6$ giving a molecular weight of 227.134 and an oxygen balance of -74%, illustrating that there is not enough available oxygen in TNT for complete combustion during detonation [1].

So far the discussion has focussed on energy released during detonation. For oxygen deficient explosives (i.e. negative oxygen balance), additional post-detonation energy is available through further combustion of the detonation products as the fireball expands and mixes with ambient oxygen. Such reactions are known as explosive afterburning. The amount of energy available (heat of afterburning ΔH^0_{AB}) can be estimated as the difference between the heat of combustion and the heat of detonation. For TNT the heat of detonation is 4.6MJ/kg and the heat of afterburn is 10.6MJ/kg [1]. The actual amount of afterburning energy released in the fireball will depend upon details of how the detonation products expand and mix with ambient oxygen. Some explosives (such as those for use underwater or in confined spaces) contain compounds such as Aluminium, which are designed to actively promote explosive afterburning. Many explosives exploit afterburning to produce a blast wave with relatively large positive phase duration, often referred to as "pushing" rather than "cracking" explosives.

3. Blast Waves

The rapid expansion of the detonation products creates a shock wave in the surrounding medium, which for simplicity we will assume is ambient air. This shock wave in air is known as a blast wave. Similar to the detonation wave discussed earlier, there is for practical purposes, a discontinuous increase in pressure, density, temperature and velocity across a blast wave. The shock-induced compression of the ambient air also leads to an increase in temperature behind the shock front. The pre and post shock states are described by conservation equations for mass, momentum and energy, collectively known as the Rankine-Hugoniot Jump equations [1], [2].

Figure 2 shows a typical static pressure-time curve for a blast wave. Static pressure is sometimes also referred to as side-on pressure because in order to record static pressure, the gauges are mounted side-on to the direction of travel of the blast. In Figure 2, t_a is the time of arrival of the blast wave, P_s is the peak pressure of the blast wave and P_a is ambient pressure. The discontinuous pressure rise at the shock front is shown by the jump in pressure from P_a to P_s at time t_a. It is often convenient to express blast pressure as an overpressure, i.e. the pressure increase above the ambient level. Figure 2 shows an approximately exponential decrease in pressure until the pressure drops down to the (pre shock) ambient level at time $t_a + t_d$. The duration for which the pressure is greater than ambient is referred to as the positive phase, and therefore the negative phase describes the duration for which the blast pressure is below ambient. In addition to the blast pressure, another important parameter related to damage is the positive phase impulse, which is simply the integral of pressure during the positive phase,

$$I = \int_{t_a}^{t_a+t_d} P(t)dt$$

where P(t) is overpressure as a function of time. Normally, this integral is determined by calculating the area under the curve with an approximation such as the trapezoidal method.

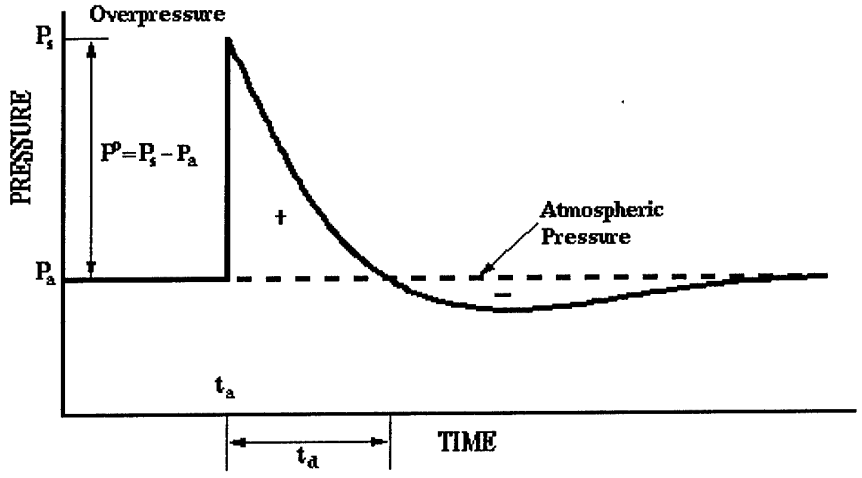

Figure 2. Typical pressure–time curve for a blast wave [2].

3.1 Shock Reflection

The interaction of a shock with a surface can be quite complex, hence the geometry and the state of the incident shock are quite important when studying blast interaction with surfaces. This section provides a brief description of some important considerations when investigating blast loading on surfaces.

When a shock undergoes reflection, its strength can be increased significantly. The magnification is highly non-linear and depends upon the incident shock strength and the angle of incidence β. One can define a reflection coefficient Λ as the ratio of the reflected overpressure ($P_r - P_a$) to the overpressure in the incident shock ($P_s - P_a$), where P_r is the peak pressure of the reflected shock wave. Figure 3 from Kinney and Graham[2] illustrates how the reflection coefficient varies as a function of angle of incidence (0° corresponds to normal reflection) and initial shock strength measured in terms of the Mach number of the shock (M_x = shock velocity/speed of sound in ambient air). The Mach number of the incident shock M_x is related to incident pressure by,

$$\frac{P_s}{P_a} = \frac{1}{6}\left[7M_x^{\,2} - 1\right].$$

For a strong shock (i.e. large Mach number), the maximum reflection coefficient is about 8 for a normal reflection. However this assumes ideal gas conditions, which may not be valid for a strong shock that generates a large temperature and pressure jump. In this case, the reflection coefficients can be as large as 20. For shocks with M_x>1.5 Figure 3 shows dramatic changes to the reflection coefficient at an angle of incidence of 39.23^0. At angles of incidence of 39.23^0 or less, the reflected shock will interact with the incident shock to form a Mach stem. It is beyond the scope of this report to discuss Mach stems in detail and the reader is directed to the reference [2] for further information on Mach stems.

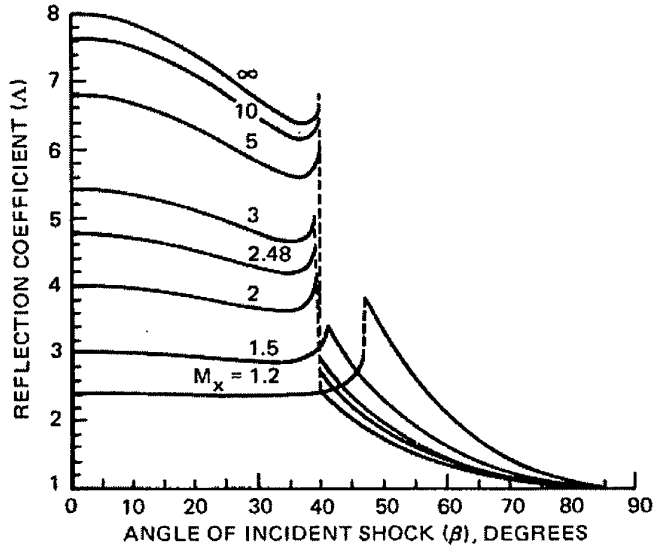

Figure 3. Reflection coefficient as a function of incident angle and initial shock strength [2].

4. TNT Equivalent Weight

Equivalency values are often used to relate the performance of different explosives. The TNT equivalent for an explosive, is the mass of TNT that would give the same blast performance as the mass of the explosive compound in question. Tables of values may be found in ConWep[5], Baker et al.[4] or Cooper[1]. Understanding the tests used to generate equivalency factors is very important. Charge geometry, munition casing, afterburning, and interaction with the target, all have an influence on the blast performance of a weapon. Different tests will often produce different equivalency factors for each parameter of interest. For example, ConWep[5] gives values of 1.11 and 0.98 for determining the equivalent mass of Composition B required to give the same peak overpressure and positive phase duration, respectively as TNT. Therefore, equivalency factors are useful, but one must be aware of the limits of practical application.

5. Equivalent Bare Charge

Many warheads and munitions utilise a combination of blast and fragmentation to damage a target. The casing of these weapons may be naturally fragmenting or may be constructed with pre-formed fragments. The fragmentation process absorbs a significant portion of the explosive energy, which decreases the energy available to generate blast. This means that a cased weapon will produce a weaker blast than an uncased weapon with the same mass of high explosive. The blast of a cased weapon can be estimated using Equivalent Bare Charge (EBC), which is defined as the amount of bare explosive that would produce the same blast as the cased weapon.

Several methods exist for estimating EBC. Two of the most commonly used equations are the Fisher equation and the modified Fisher equation [7]. As discussed in [7], it is believed that Fisher provides a reasonable estimate of EBC for warheads with thick, scored cases or very large fragments and modified Fisher provides a better estimate of EBC for weapons with cases that provide less confinement such as pre-formed fragments.

The Fisher and modifed Fisher equations [7] are:

$$EBC_{Fisher} = C\left(0.2 + \frac{0.8}{1+\frac{M}{C}}\right) \qquad EBC_{modified\ Fisher} = \frac{1}{2}\left[C + C\left(0.2 + \frac{0.8}{1+\frac{M}{C}}\right)\right]$$

where EBC = Equivalent Bare Charge (kg),
C = Mass of high explosive (kg),
M = Mass of the casing or fragments (kg).

6. Cube-root Scaling

Much of the published data for blast wave parameters is presented in terms of scaled distance. This is convenient since data from many explosive tests can be combined into a single chart or table. Cube-root scaling is attributed to Hopkinson, who postulated that blast wave parameters such as overpressure would scale with the cube root of explosive mass. At a range of R_1 from a reference explosive of mass M_1, an overpressure of P will occur, according to cube-root scaling, if the explosive mass is changed to M_2, the same overpressue will occur at a distance R_2 [6]. Scaled distance Z is given by,

$$Z = \frac{R_1}{W_1^{1/3}} = \frac{R_2}{W_2^{1/3}}.$$

Cube-root scaling is the simplest and most common form of scaling, but it is only applicable to identical explosive types and charge shapes. For explosions at high altitude, Sachs scaling is used to account for variation in ambient conditions. Kinney and Graham[2] have refined Hopkinson and Sachs scaling laws into a single set of scaling laws for general application.

7. Conclusion

Blast effects can play a significant role in target damage. This work has outlined how explosive shocks are formed, and what factors affect the output shock that will be delivered to a target. It is hoped that this document has provided sufficient background for a non-specialist to grasp the fundamental concepts that need to be considered when studying weapons containing explosive warheads. For further details the reader is directed to the list of references.

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19. ABSTRACT

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